Materials Sciences Corporation

COST/PERFORMANCE MODELS FOR COMPOSITE AIRCRAFT AND MISSILE STRUCTURES

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TABLE OF CONTENTS

1. SUMMARY

Innovative design tools are required to identify potential new material candidates for missile and airframe structures. Emerging material technologies, in the form of new material systems and new fabrication processes, provide the motivation to review classic evaluation methodologies. Existing forms of component optimization are one-dimensional; implicitly regarding the cost associated with raw materials and component fabrication as a constant. The advent of new, more cost effective materials and processes necessitates the coupled consideration of both structural optimization and minimized cost.

The Phase I proposal had identified the potential business opportunity for the development of an integrated structural/cost optimization tool. There is an available niche in the analysis market for software with this dual capability. Additionally, the creation of a capability in this area will provide the DoD community with a unique tool for evaluation of potential candidates for material substitution. The Phase I program focused on identifying typical structural configuration, investigating cost prediction algorithms, and performing structural optimizations with existing industry structural optimization software. The following paragraphs summarizes the work performed in this Phase I.

The Phase I systems integrator, McDonnell Douglas Aerospace (MDA), identified two composite aerostructures as candidates for evaluation. The F-18 Wingbox and the LCCW Advanced Dispenser Weapon provided two baseline components containing several multi-parameter optimization opportunities. These components had elements demonstrating cost, weight, geometric optimization, and structural performance considerations. This approach allowed the selection of a particular component, e.g., stiffened panel, for use in evaluating existing algorithms for optimization performance. The optimization routines used in these evaluations were PASCO (Panel Analysis and Sizing Code) [1], and Mechanica (P-Element Finite Element Code with Optimization) [2].

The PASCO code was selected for an in-depth weight optimization of a compression panel using typical stiffener designs. The resulting weight optimized panels then went through a cost analysis developed by McDonnell Douglas Aerospace. The cost analysis was useful in identifying the relative cost of raw materials, hand labor, and tooling. It is evident from the results of this study that material cost alone is a small percentage of the cost of an aerospace structure. The studies showed the value of a rigorous approach to costing, in which the geometric fea-

tures and number of manufacturing operations particular to a structure are associated with a cost algorithm.

The Mechanica code was used in a study of a missile body structure, and a demonstration of shape optimization. Results of these studies identified that Mechanica can perform useful trade studies for localized geometric variations. Greater flexibility is required to allow the redefinition of interference caused by interconnecting geometries. Additionally, computational requirements for small models can be severe. This implies that in the effort to attain overall generality of the Mechanica code, case specific applications may suffer from ambiguous solution techniques.

Additional studies clearly demonstrated that cost and weight optimization cannot be treated separately. A simple example using a sandwich construction was used to demonstrate that cost and weight must be treated as a combined objective. None of the existing software packages evaluated in the Phase I is currently capable of performing simultaneous optimization of cost and weight. In addition, there are many shortcomings in the way composite structures are typically handled in optimization codes. For these reasons, an approach for an integrated optimization code is outlined for the Phase II effort. This code would combine the best features of current optimization programs, along with more realistic treatment of composite construction, and integral costing algorithms. The code would be written for a Windows system, with a strong emphasis on ease-of-use features. Extensive planning has gone into the definition of this product, which is summarized in this report.

2. PROGRAM GOALS & APPROACH

As composite materials continue to evolve, new material systems and processes are continually introduced. The choice of a material system usually involves balancing cost and performance. Over the years, tools have been developed with the goal of optimizing structural configuration to minimum weight or other easily quantifiable objectives. These tools help with the performance side of the equation, but there are few computerized aids that address cost issues. Without such a tool, it is nearly impossible for an engineer determine the relative advantages of materials in terms of both cost and performance during the early design phases of a project.

It is evident that the required tool will involve a form of optimization. Using automated optimization, the engineer would be able to quickly evaluate how changes in a material, or material system constituent, affected the structural arrangements and thicknesses. The combination of material change, and resulting structural arrangement change will in turn influence the cost. By combining cost and weight into a single objective, one could find optimal structures that are designed with a cost goal in mind.

With these challenges in mind, the goals of this program are as follows:

- Develop an approach for integrated cost/performance modeling
- Demonstrate the validity of the approach via preliminary studies
- Establish a vision for Phase II and Phase III products

These objectives were realized by a team of Materials Sciences Corporation (MSC) and McDonnell Douglas Aerospace (MDA). MDA's Advanced Structures and Manufacturing Group provided information on representative structures, provided a cost modeling approach, and performed cost studies on typical composite constructions.

The Phase I program was broken down into the following tasks:

- Task I Identify Candidate Components
- Task II Identify Materials and Methods
- Task III Develop a Modeling Approach
- Task IV Perform Trade Studies

Results of each task are reported in the following sections.

3. RESULTS

3.1 TASK I IDENTIFY CANDIDATE COMPONENTS

MDA supplied information on two composite aerospace structures, and F-18 wing box and the body of an air-launched missile. The F-18 and the LCCW missile body (Figure 3-1 and Figure 3-2) provided candidate component elements for optimization.

An understanding of the analytical requirements for cost and weight optimization were gained through specific studies on elements of these composite constructions. For example, a series of stiffened compression panels were analyzed (Section 3.4). While geometrically simple compared to a complete wing box, these panels demonstrated many of the challenges a cost and weight optimization tool would have to meet.

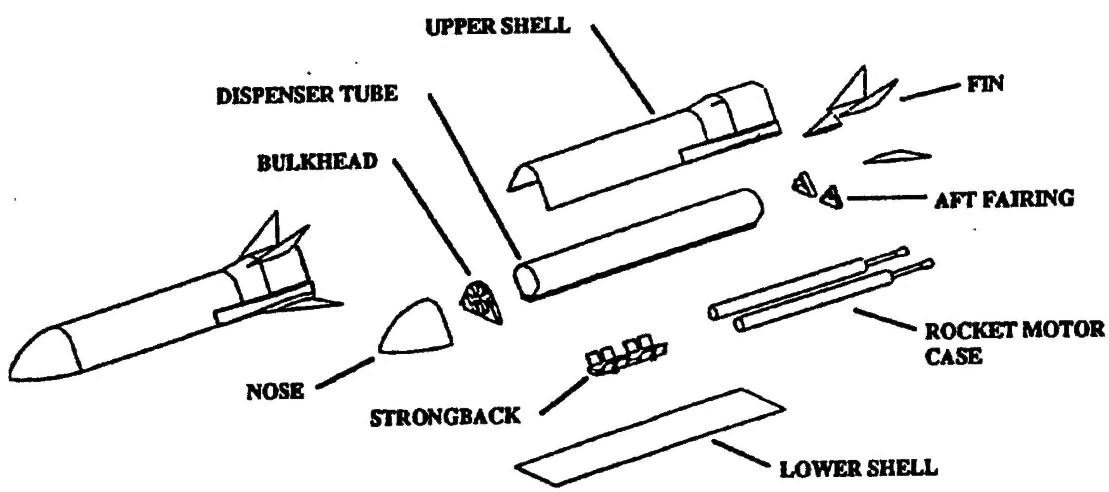


Figure 3-1 Configuration of LCCW Advanced Dispenser Weapon

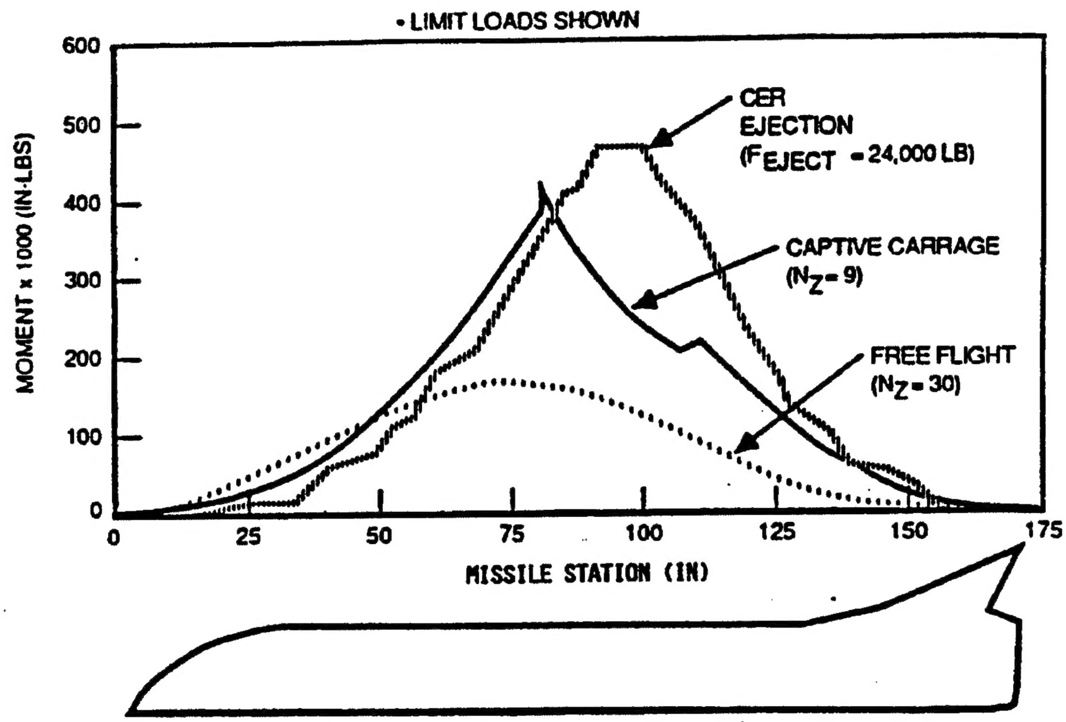


Figure 3-2 Design Body Bending Moments for LCCW Missile

3.2 TASK II IDENTIFY MATERIALS AND METHODS

In order to make the studies realistic, actual materials that might be involved in a trade analysis were identified by Naval Air Warfare Center, Aircraft Division (NAWCAD). Properties for these materials are given in Table 3-1. Material A is a 4-harness satin weave, while materials B and C are tape prepregs. A decision was made to focus on prepreg materials for the Phase I activities. Clearly, many of the cost saving opportunities are in alternate processes and material forms. One goal of a Phase II program is to build in the flexibility to deal with new and evolving process technologies.

Table 3-1 Candidate Materials Identified by NAWC for Use in Studies

Matl	E_1	E_2	ν_{12}	G_{12}	F_1^T	F_1^C	F_2^T	F_S	ρ
	Msi	Msi		Msi	ksi	ksi	ksi	ksi	g/cm^3
A	10.1	9.4	0.01*	0.70	121	121	121*	14.6	1.55*
B	24.2	1.25	0.33	0.85	338	287	8.2	11.8	1.55
C	24.4	1.35	0.33	0.75	371	235	7.3	11.6	1.55*

* assumed value

3.3 TASK III DEVELOP A MODELING APPROACH

3.3.1 Cost Models

Predicting cost requires a combination of first-principles analysis and use of an empirical database. The first-principles analysis is used to identify and quantify all of the cost drivers in the fabrication of a structure. One driver is obviously the raw material costs. However, this represents only a small portion of the total costs. Labor costs are driven by the number of plies that must be placed, the amount of cutting required, and the difficulty of placing the plies. The difficulty factor is a function of the number of bends in the ply, whether the surface is concave or convex, along with other parameters. Once all of the cost drivers are quantified, a database of empirical time studies information must be used to associate the operations with the time required, and thus the labor cost. Tooling costs can be generated in a similar manner. The per-part material and labor costs cannot be added directly to the tooling cost unless the number of parts that will be made per tool is known.

MDA has developed costing algorithms based on these principles. Figure 3-3 shows a flow diagram for a generic cost model. A similar costing approach was applied to the studies reported in Section 3.4.2.

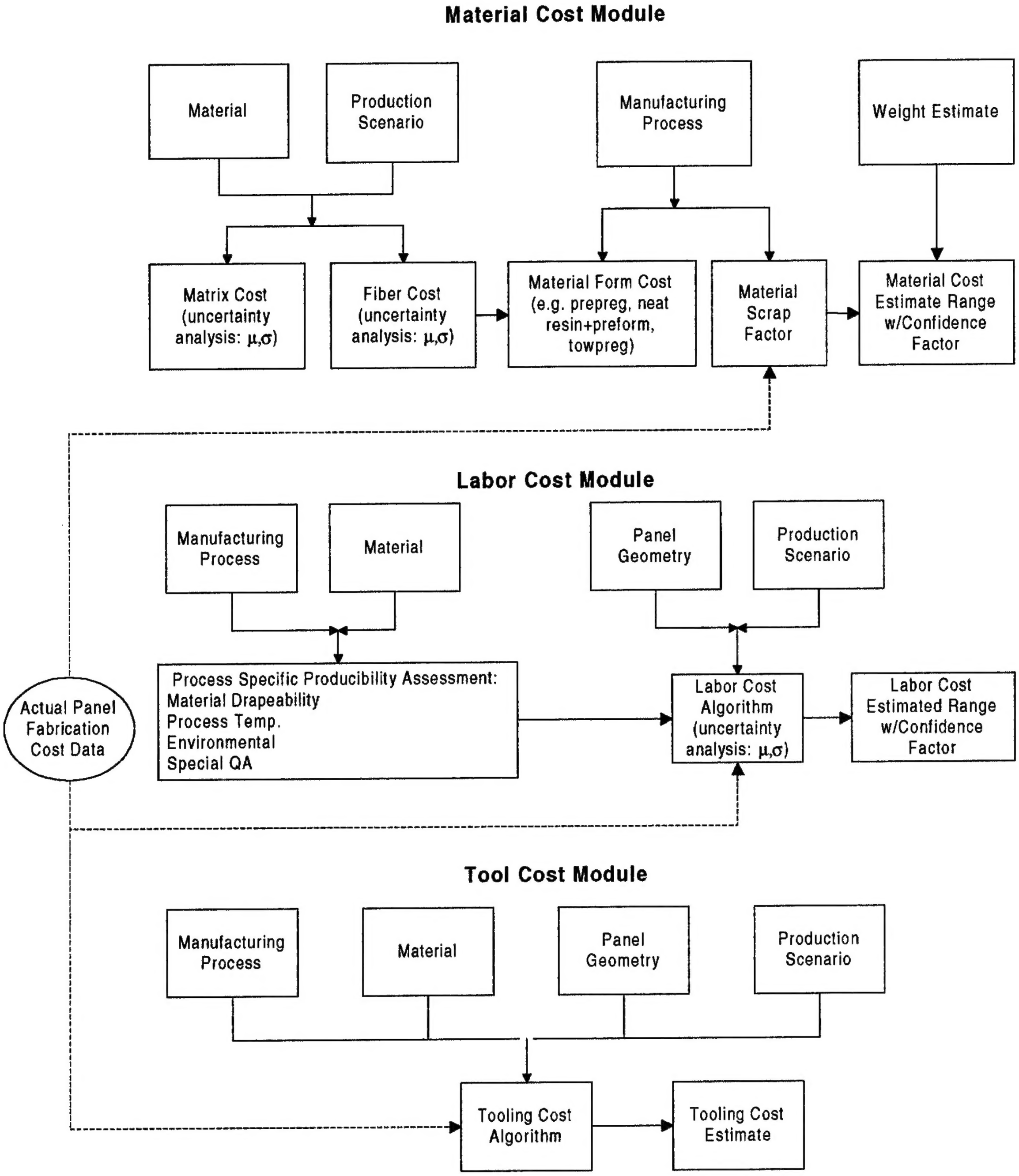


Figure 3-3 MDA Analytic Approach for Cost Model Development

3.3.2 Simultaneous Optimization of Cost and Weight

To show some of the important aspects of combining cost and weight in an optimization process, consider a sandwich panel under compression. The design variables are the thickness of the skin laminates, and the thickness of the core. For the example, only buckling constraints are considered. The example is constructed using the following data:

Facesheet Young's Modulus = 7 Msi, v12=0.35, Quasi-isotropic lay-up

Core Modulus = 0

Panel Dimensions = 100 in. X 100 in.

Required Load Intensity = 10,000 lb/in

Density: Facesheet = 0.051 lb/in^3, Core = 0.0058 lb/in^3

Cost: Facesheet = \$30/lb, Core = \$10/lb

The panel is assumed to be simply supported on all edges.

The solid curve in Figure 3-4 is a constraint curve that divides design space into two regions; everything above and to the right of the curve will not buckle under the required load, and everything below and to the left will buckle. The dashed lines in the plot give contours of constant weight. The weight optimized will be on the contour closest to the origin, and also on the constraint curve.

Figure 3-5 is a similar plot, but this time with contours of constant cost. Because the slope of the cost contours is different, the cost optimized design is different from the weight optimized design.

Cost and weight can be combined if one assigns a cost value to saving weight. For example, if saving a pound of weight is worth \$200, then a combined objective function (the quantity being minimized during the optimization), can be written as

$$P_{combined} = 200 \text{ x weight} + \text{cost}$$

Figure 3-6 shows the constraint curve once again, this time with contours of effective cost ($P_{combined}$). The optimized design is once again different. The actual optimized points are given in Table 3-1.

The example demonstrates clearly that cost should not be calculated as a separate step after a weight optimization. Rather, cost and weight must be treated simultaneously.

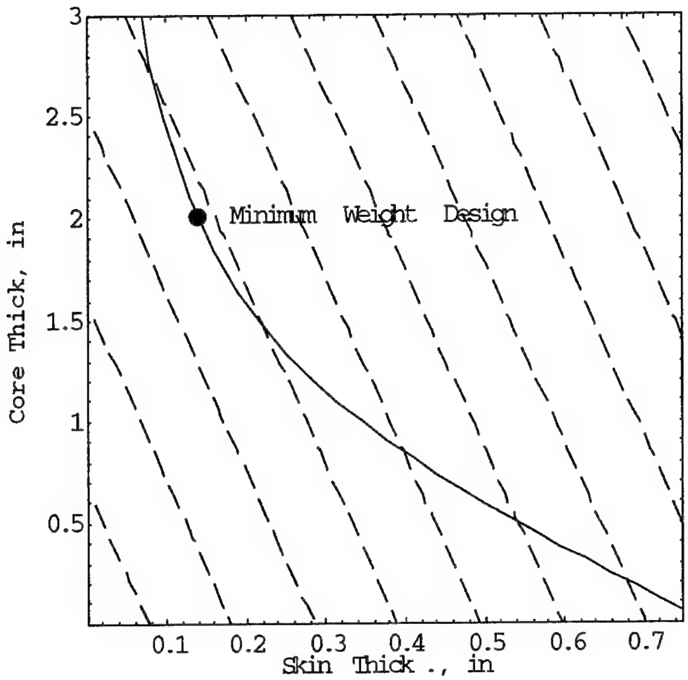


Figure 3-4 Sandwich Panel Buckling Constraint Versus Design Variables. Dashed lines are contours of constant weight.

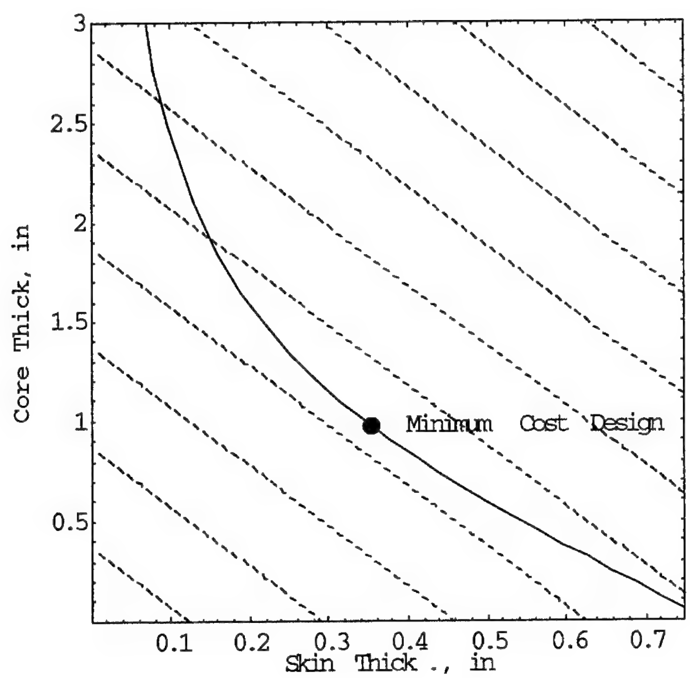


Figure 3-5 Sandwich Panel Buckling Constraint Versus Design Variables. Dashed lines are contours of constant cost.

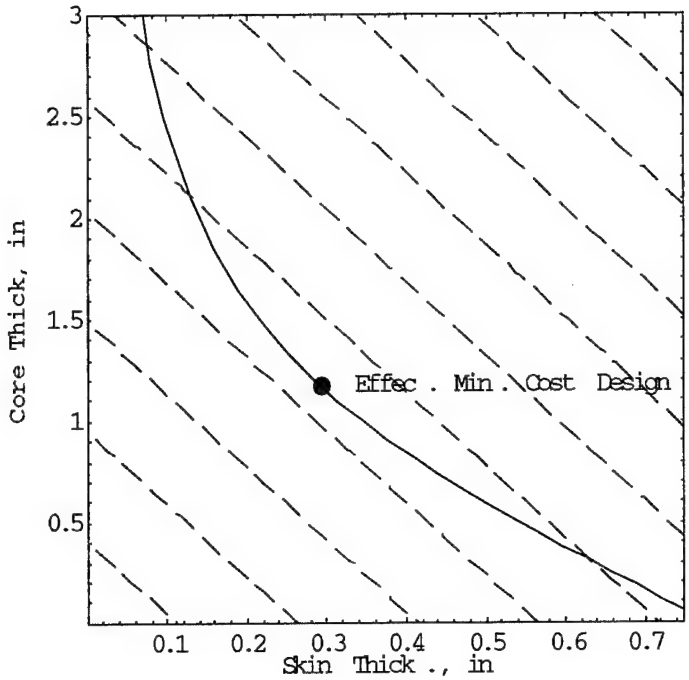


Figure 3-6 Sandwich Panel Buckling Constraint Versus Design Variables. Dashed lines are contours of combined weight and cost objectives.

Table 3-1 Optimized Designs for Different Objectives

	Skin Thickness	Core Thickness
Minimum Weight Design	0.138	2.007
Minimum Cost Design	0.354	0.968
Combined Cost & Weight	0.292	1.171

3.3.3 Optimization Engines

Two optimization tools were investigated during Phase I - PASCO [1] and Mechanica [2]. These codes were selected as representative of the state-of-art in optimization for composite structures.

It should be noted that a number of codes also exist which may be integrated with standard finite element packages including MSC/NASTRAN and SDRC IDEAS Master Series. Alternatively, one may use generic optimization package such as CONMIN [3] to create a user specific tool. CONMIN is a collection of subroutines that will perform an optimization, given a link to any analysis package, and a definition of the design variables. The choice was made during Phase I to investigate integrated packages such as PASCO and Mechanica rather than devote time and resources in a programming effort to link CONMIN with a specialized analysis module.

PASCO (Panel Analysis and Sizing Code) was developed by NASA specifically for stiffened composite panels. PASCO treats structures that are prismatic, *e.g.,* constant in cross-section along one coordinate. It has a unique analysis module that uses exact elements. In an exact element, closed-form solutions to the governing differential equations for a plate are computed. Boundary conditions to the differential equations are satisfied along the lines where elements connect. Because of the exact solution, a single element is needed to model any uniform segment of the model; there is no discretization error. This feature is important during optimization because no remeshing of the model is ever required. In addition, with an exact element, it is easy to obtain the analytic derivatives with respect to the design variables needed for an efficient optimization. PASCO incorporates the CONMIN algorithms discussed above and in [3] to perform the optimization. The code is capable of treating both strength and buckling constraints.

It should be noted that although the solutions in PASCO are exact, the code execution can be time consuming. The "exact" solutions require numerically solving a large system of transcendental equations which can be computationally intensive. PASCO does have the ability to define a single stiffener as repeating element, or superelement. Once the stiffener is defined, it is easy to form a panel with as many bays as necessary, using the repeating element. Internally, the stiffness of the repeating elements is generated only once, making the analysis more efficient.

Mechanica is a general purpose finite element code which uses the P-element approach. In conventional finite elements, mesh refinement is used to converge to the exact solution. In a P-element approach, the degree of the polynomial approximation in each element is increased in order to obtain convergence. The advantage of P-element approach is that single elements may represent a large area, thus simplifying the remeshing problems that may occur during an

optimization. In addition, the elements in Mechanica may have edges that are conic sections, such as an arc segment. Again, this simplifies using geometric variables in an optimization.

Mechanica was not designed specifically for the analysis of composite materials. The code can include orthotropic, and anisotropic materials, however, the layered nature of a composite cannot be directly treated in the code. Individual material properties may be a design variable, but the interaction between properties that occurs when one changes a stacking sequence, or a constituent property cannot be represented. Mechanica has a strong graphical interface that allows the user to rapidly create a model, assign design variables, and perform an analysis or an optimization. While this makes the code easy-to-use, it also restricts the user in the nature of problems that may be solved. If a pre-defined form does not exist to perform the operation desired, there is no way to bypass the graphical interface.

3.4 TASK IV PERFORM TRADE STUDIES

3.4.1 Weight Optimization Using PASCO

A minimum weight optimization was carried out using the PASCO code on a series of composite panel designs. Three distinct stiffener geometries were analyzed; a blade stiffener, J-stiffener, and Hat-stiffener. One advantage of PASCO is that realistic constraints on the ply paths can be applied. For example, the plies that form a blade may wrap around a radius and also form the top plies of the attached flange. This type of construction is easily modeled in PASCO by mathematically coupling the thickness of layers in the blade and flange area. The design constraints are buckling and strength. The material strengths in Table 3-1 were converted to fiber direction strains so that the laminate could be changed during the optimization process. Optimized panels were found for each of the material forms in Table 3-1.

The example problem required the panels to support a compressive load of 5000 lbs/in and a pressure of 5 psi. The panels were 30 in. long in the stiffener direction. To maintain a common basis for comparison, the panels were always 8 bays wide in the transverse direction. Because the width of the bays could vary, the total width of the panel changed between designs. However, by presenting weight on a areal basis, the effect of this change is taken into account.

Figure 3-7 through Figure 3-9 show the optimized panels for material "C". Like most optimization codes for composite laminates, PASCO treats the thickness of a single ply orientation

as a design variable. Thus, thickness is a continuous variable, rather than the discrete thickness imposed by the lamination process. In the example problems, the continuous thicknesses were converted to a discrete number of plies by an iterative process. After an initial run of the code, ply groups with a thickness close to a multiple of a ply thickness were rounded to the multiple value. The thickness of these groups was then fixed, and the problem rerun. The process was repeated until an integer multiple of the ply thickness was obtained, while keeping all of the constraints satisfied. This process was found to be tedious, and does not necessarily give a true optimum.

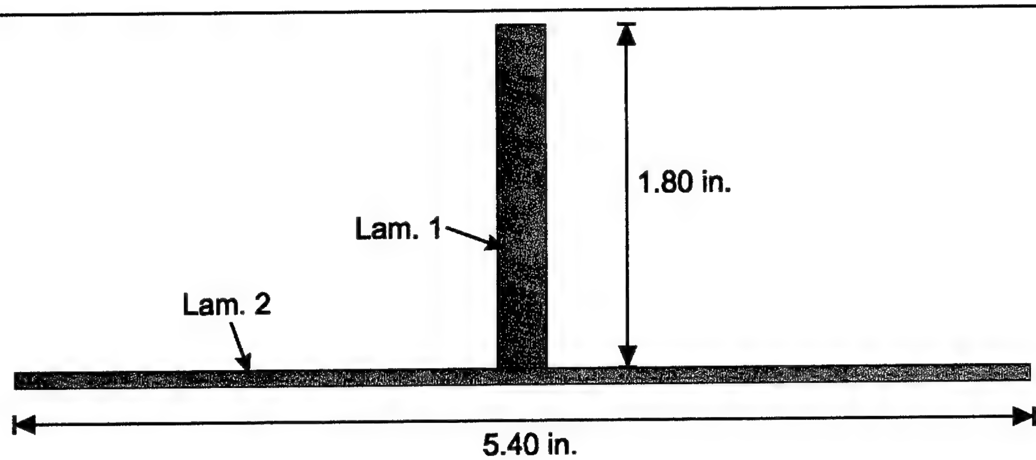
Figure 3-10 through Figure 3-12 show the buckling modes for these optimized panels. In each case, the critical mode is an overall panel buckling. In some cases, it is desirable to have the lowest mode local to the bays. This allows for some post-buckling strength.

Figure 3-13 summarizes the weight results from study, using the material properties from Table 3-1. From these results, the following conclusions can be drawn:

- For the tape materials, the J-stiffener was the lightest
- For cloth, the blade stiffener was best
- The J-stiffener was insensitive to which tape was used (buckling critical)
- The discrete hat stiffener was most sensitive to the tape selection (strength critical)

It must be noted that these results are a function of the load intensity (and load components) chosen for the example. It can be shown that the relative merit of different stiffener forms changes with load intensity.

A series of runs were also made using generic materials in which the fiber direction allowable strain was varied between 4000 μin/in to 6000 μin/in, and the fiber direction modulus varied between 20 Msi and 40 Msi. These runs were performed to measure the sensitivity of the results to material property changes. The results are summarized in Figures 4-9 through 4-11. As expected, designs that were buckling critical (J-stiffener) are most sensitive to changes in modulus, while designs that are strength critical (Hats) are most sensitive to changes in allowable strain. A strain limited structure will obviously benefit from either an increase in modulus (for a specified load intensity), or an increase in strain allowable.



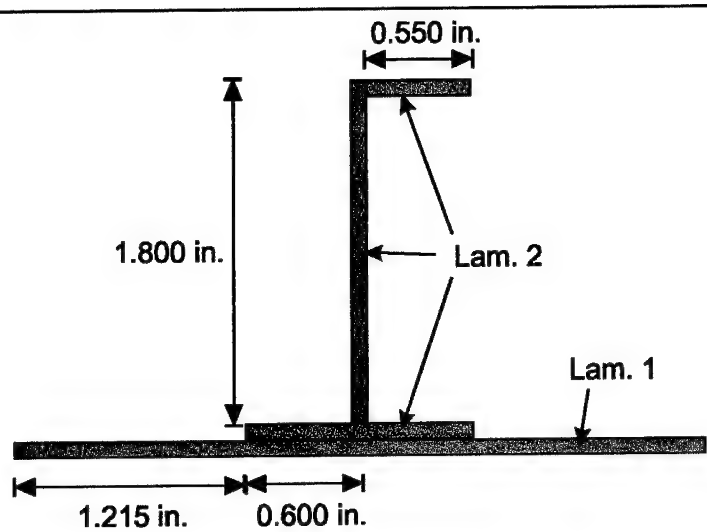
Laminate 1: $(45/90/-45/0/-45/45/0_2)_s$ - 0.80 in. thick

Laminate 2:

$(45/90/-45/0/-45/45/0_2/45/-45_2/45/90/45/-45/0_2/-45/45/0_2/-45/90/45/0_2/\bar{0})_s$

-0.265 in. thick

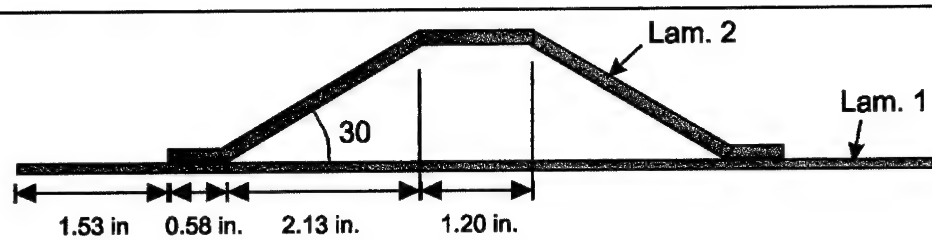
Figure 3-7 Weight Optimized Blade Stiffener Design



Laminate 1: $(90/0/90/45/-45/0/90/0/\bar{0})_s$ - 0.085 in. thick

Laminate 2: $(45/-45/90/-45/0/45/90/0/\bar{0})_s$ - 0.085 in. thick

Figure 3-8 Weight Optimized J-Stiffener Design



Laminate 1: $(45/0/-45_2/0/45/90/45/0/-45/\overline{90})_s$ - 0.105 in. thick

Laminate 2: $(45/0_2/-45/90/-45/0_2/45_2/0_2/-45/0)_s$ - 0.140 in. thick

Figure 3-9 Weight Optimized Hat-Stiffener Design

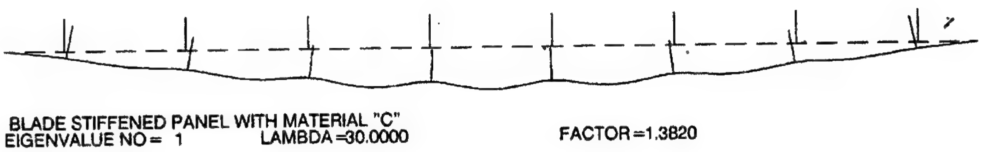


Figure 3-10 Lowest Buckling Mode for Optimized Blade Stiffened Panel

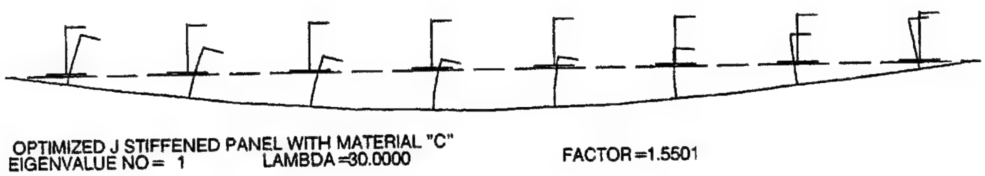


Figure 3-11 Lowest Buckling Mode for Optimized J-Stiffened Panel

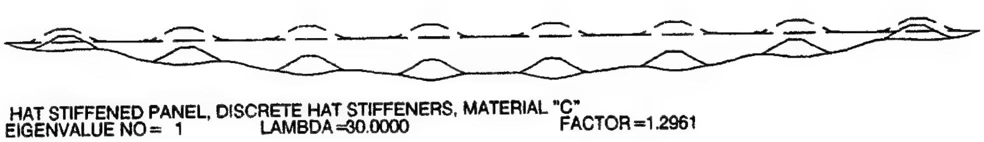


Figure 3-12 Lowest Buckling Mode for Optimized Hat-Stiffened Panel

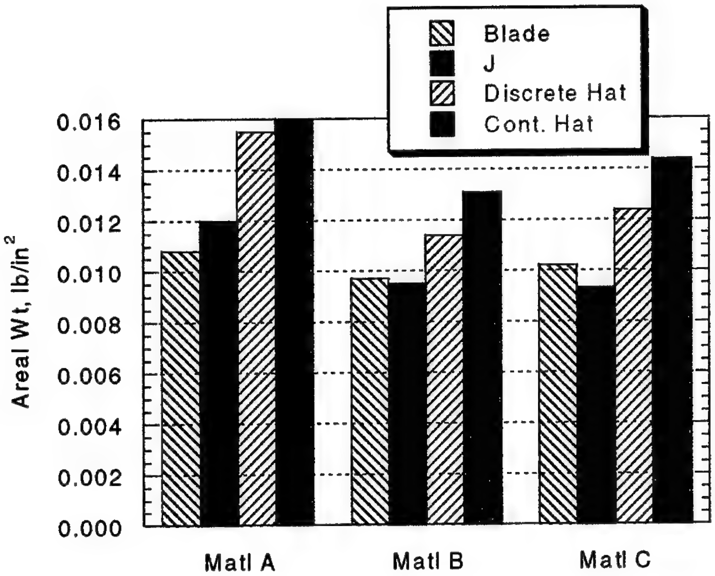


Figure 3-13 Areal Weights for Optimized Panels Using Materials From Table 3-1

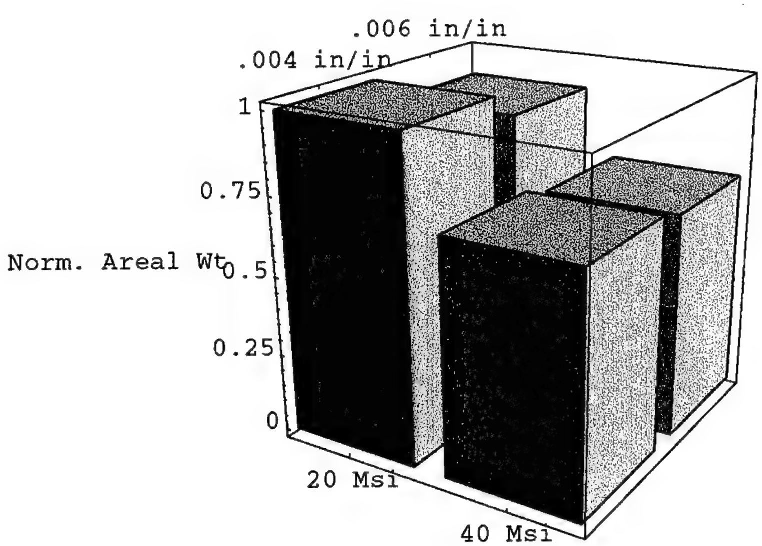


Figure 3-14 Material Sensitivity Results for Blade Stiffened Panel

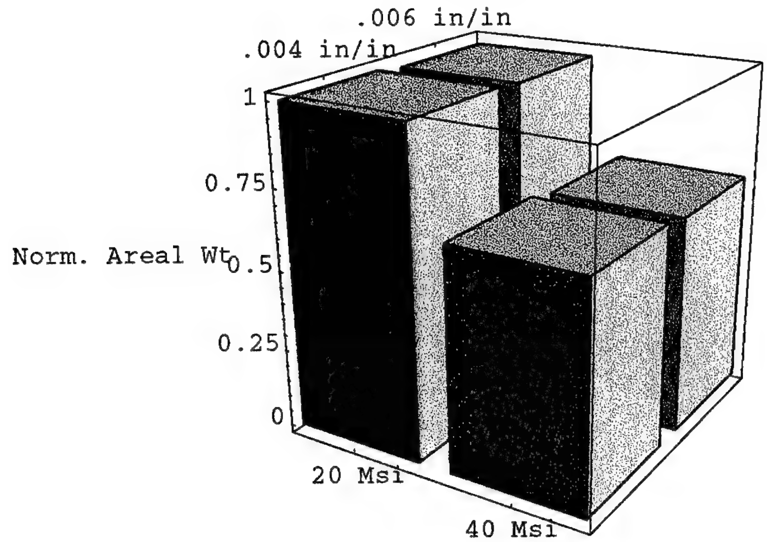


Figure 3-15 Material Sensitivity for J-Stiffened Panel

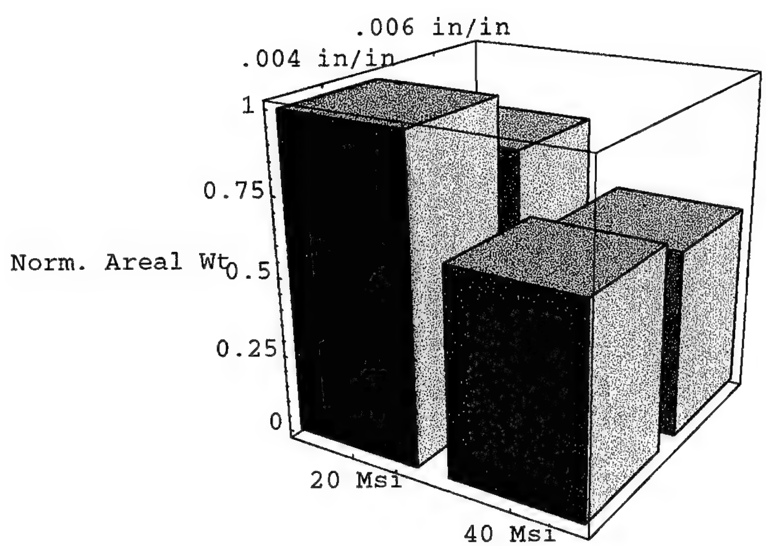


Figure 3-16 Material Sensitivity for Hat Stiffened Panel

3.4.2 Cost Studies

The design for the weight optimized stiffened panels was supplied to MDA for a cost analysis. The analysis used the following assumptions:

- 1996 Labor Rates
  - $87/hr for tooling
  - $81/hr for fabrication
- Material cost of $95/lb (IM7/977-3)
- Material utilization of 1.8
- Fabrication using prepreg

The results for fabrication cost are shown in Figure 3-17. Because the weight optimized panels had different widths, a useful comparison between stiffener types can be made by dividing the fabrication cost by the panel skin area. The figure distinguishes between material cost and labor cost. Note that the labor cost is about 75% of the total fabrication cost. It is also interesting to observe that the fabrication costs of the blade and J are similar, despite the extra bend present in the J. The tooling cost is shown in Figure 3-18. However, tooling cost cannot be directly added to the other fabrication costs without knowing how many panels can be built on a given tool (the amortization rate).

Another useful way to view this data is in the cost per stiffener. Figure 3-19 gives the labor cost per stiffener, while Figure 3-20 gives the tooling cost per stiffener. When viewed this way, it can be seen that the more complex hat stiffener is more costly to fabricate. However, in the optimized design, the hat stiffener bays were wider than for the other stiffeners. Therefore, fewer hat stiffeners are required, and the cost per unit area is actually less than for the other configurations. Tooling cost per stiffener is roughly equal.

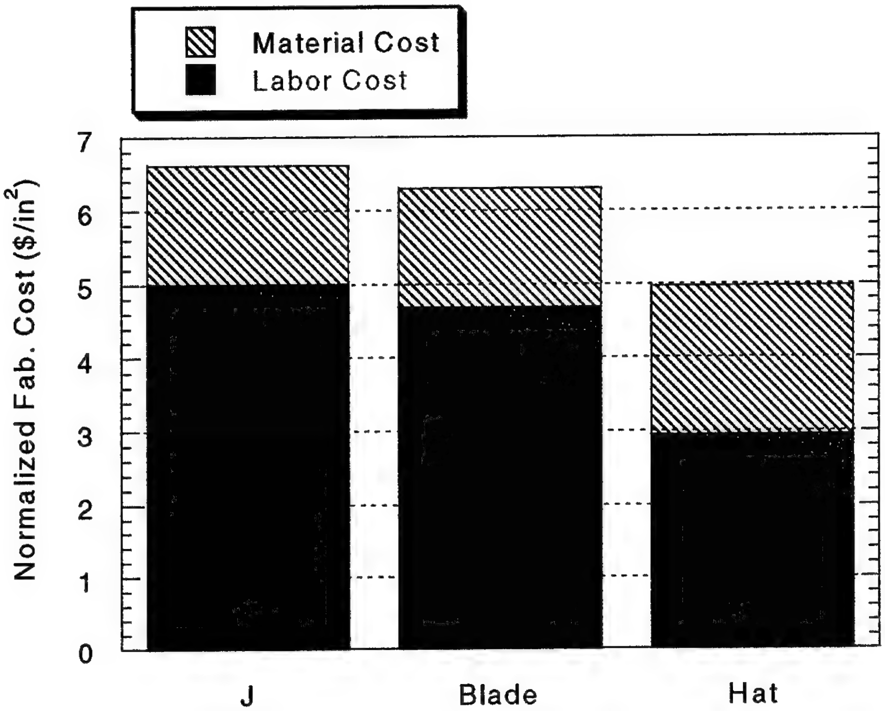


Figure 3-17 Fabrication Cost per Unit of Panel Skin Area

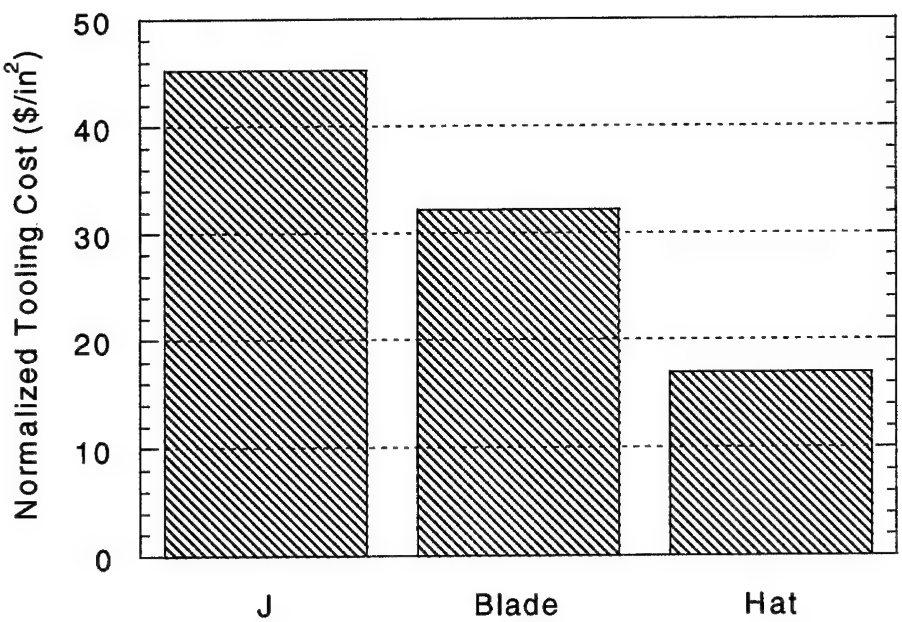


Figure 3-18 Tooling Cost Per Unit of Panel Skin Area

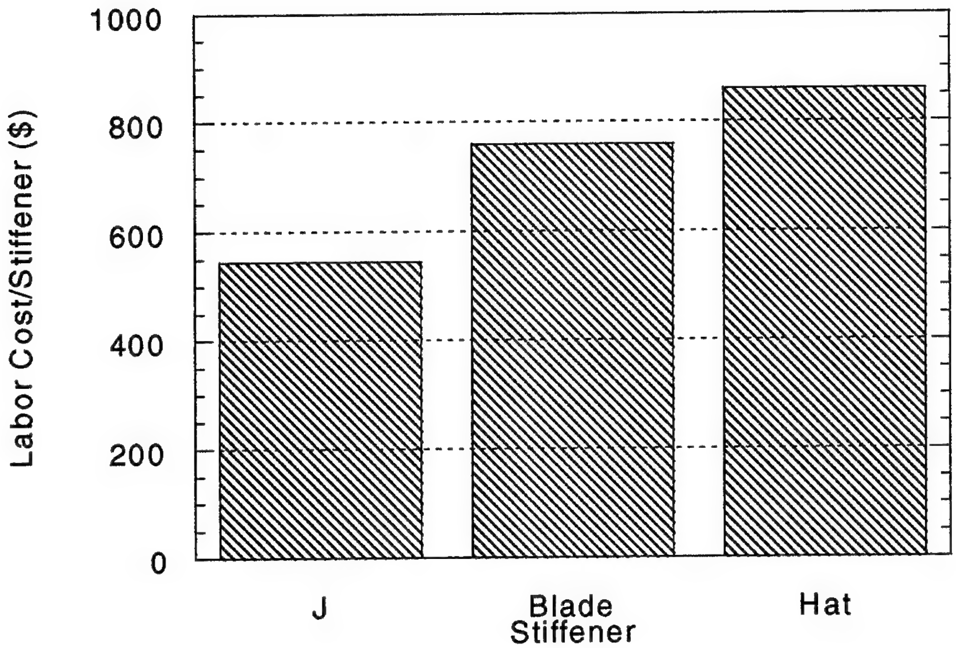


Figure 3-19 Labor Cost Per Stiffener

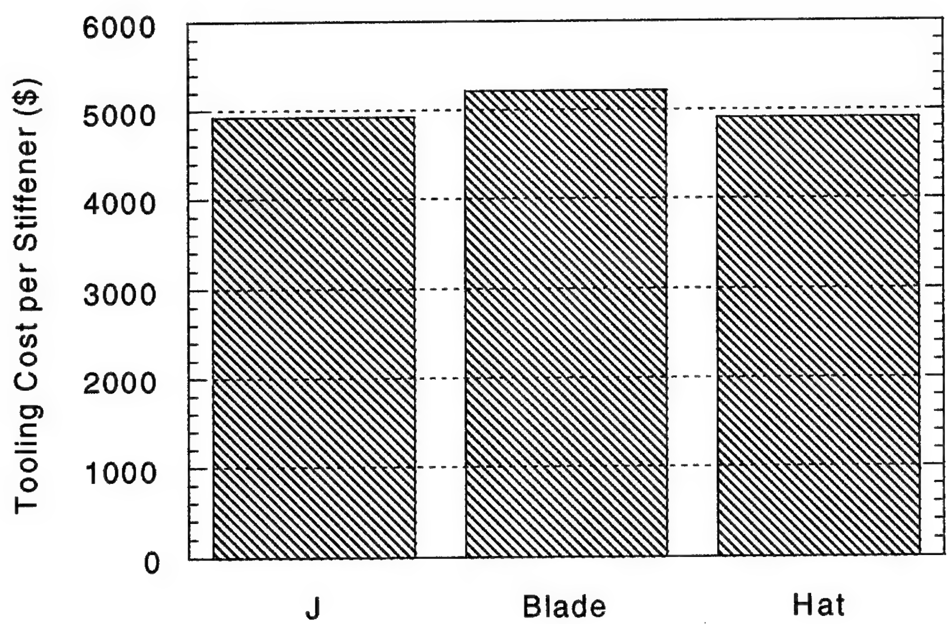


Figure 3-20 Tooling Cost Per Stiffener

3.4.3 Mechanica Optimization of Missile Shell Structure

A Mechanica model was created of the LCCW missile structure provided by MDA. For the purposes of this study, the structure was simplified to the cross-section shown in Figure 3-21, and assumed to have a constant section along the entire length. The P-element technique allows one to model this structure with just a few elements. The model is shown in Figure 3-22 with individual elements shrunken for clarity. The missile body is primarily subjected to bending loads, as shown in Figure 3-2. Similar loads were placed on the model by applying uniform pressure to the bottom shell, and simply-supporting the ends so that a peak moment of 5×10^5 in-lbs was obtained at the mid-length of the model. A simply-supported condition was simulated by constraining the ends of the shell from moving in any direction in the plane of the cross-section (x-y plane), but allowing movement normal to the plane of the cross-section.

In the optimization, the thickness of the top-shell, the bottom shell, the dispenser, and the cableway are individual design variables. The objective function is to minimize the total weight. The constraints were a buckling factor greater than 1.5, an axial stress less than 40 ksi, and a shear stress less than 30 ksi. The laminates for each of the shell sections were assumed to be identical, with the properties of a quasi-isotropic graphite/epoxy material.

The optimization history for the structure is shown in Figure 3-23. The weight of the structure dropped significantly in the first iteration. In order to move off of the constraints and change the structure further, the weight increased in the second iteration. Subsequent iterations were able to reduce the weight to some degree, but the optimizer was never able to find a design better than that found in the first iteration. The example shows that the optimization algorithm used by Mechanica does not always monotonically decrease the objective function as the iterations proceed. The search algorithm is not well documented, so it is not possible to discern exactly what is driving the execution of the program.

The history for the design constraints is shown in Figure 3-24. The graph shows that buckling was always the critical constraint.

Even though the missile was greatly simplified and modeled using only 51 elements, the optimization history shown in Figure 3-23 required over 10 hr. of CPU time on an HP 700 workstation. The short wavelength of the buckling mode forced the solution algorithm to use a large number of polynomial terms to represent the deflection, thus driving up the CPU time.

It is important to note that the real structure is designed to meet several design load conditions. In general, it is not possible to choose a "worst-case" load for a complex structure. Each

load condition imposes an additional set of constraints for the optimization problem, and the algorithm must proceed by considering all of the constraints simultaneously. This is mathematically possible, and is built into the most general optimization codes, including those using CONMIN as an optimization engine [3]. However, Mechanica does not have any mechanism for treating multiple loading conditions.

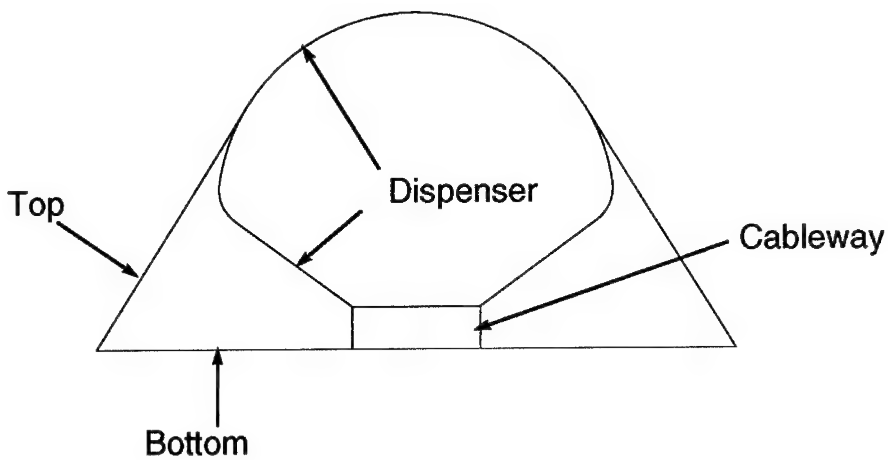


Figure 3-21 Idealized Cross-Section of LCCW Missile

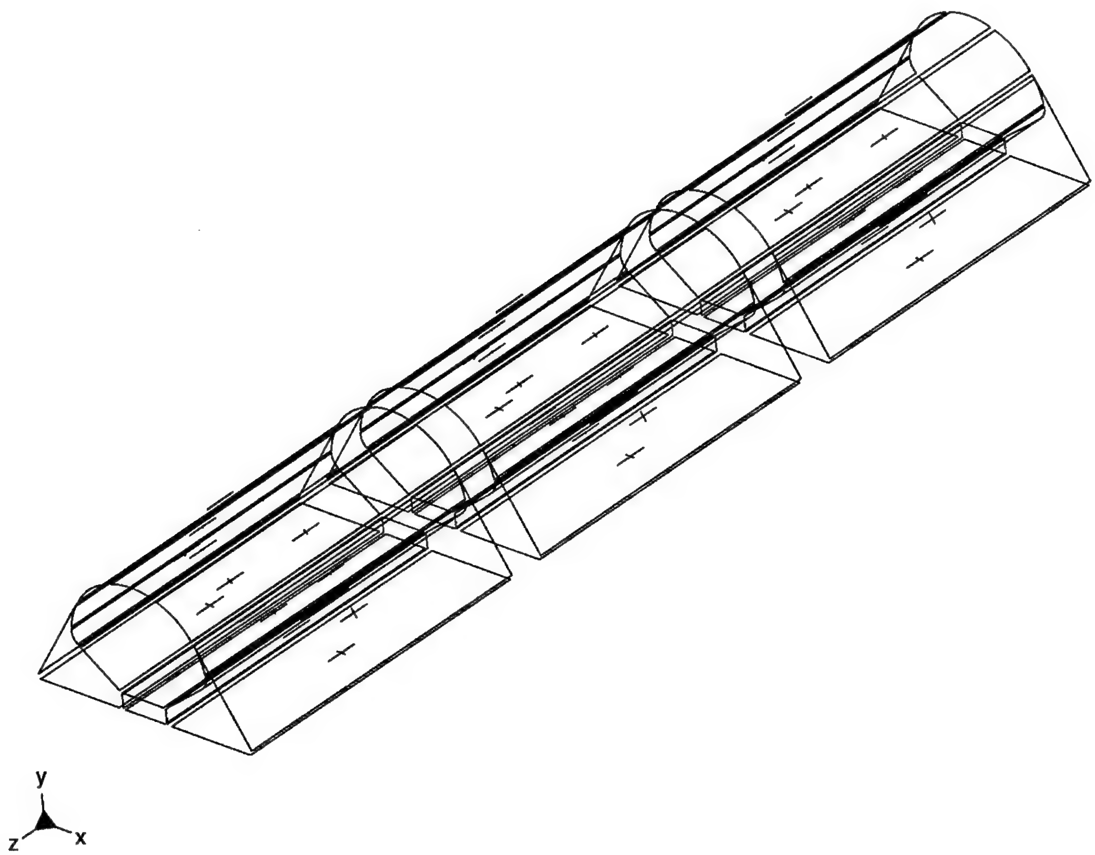


Figure 3-22 Mechanica Model of LCCW Missile, Elements Shown With "Shrink" On

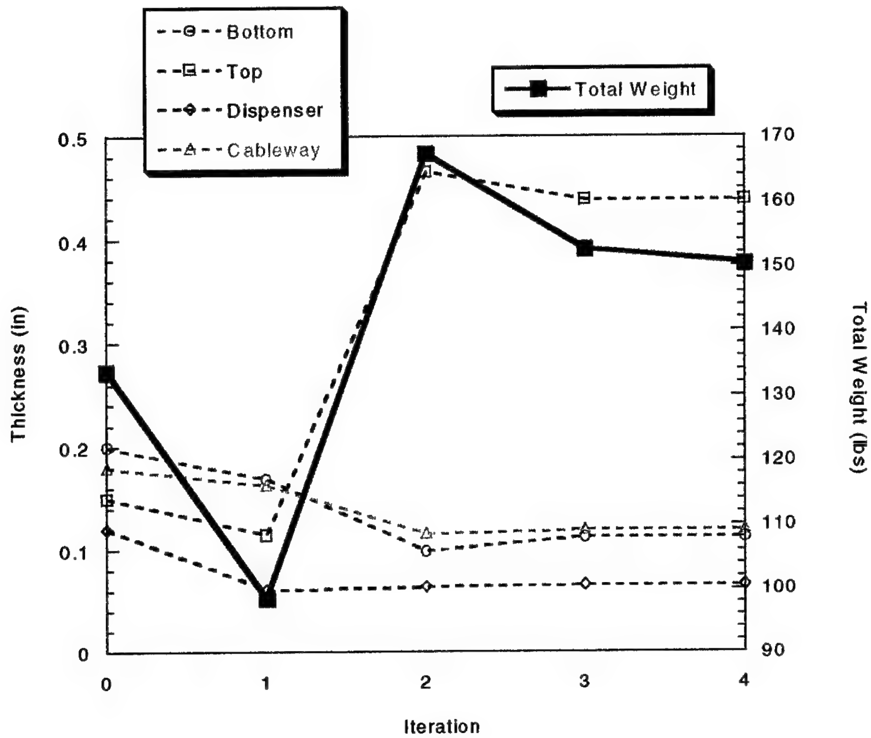


Figure 3-23 Shape History for Weight Optimization of LCCW Missile

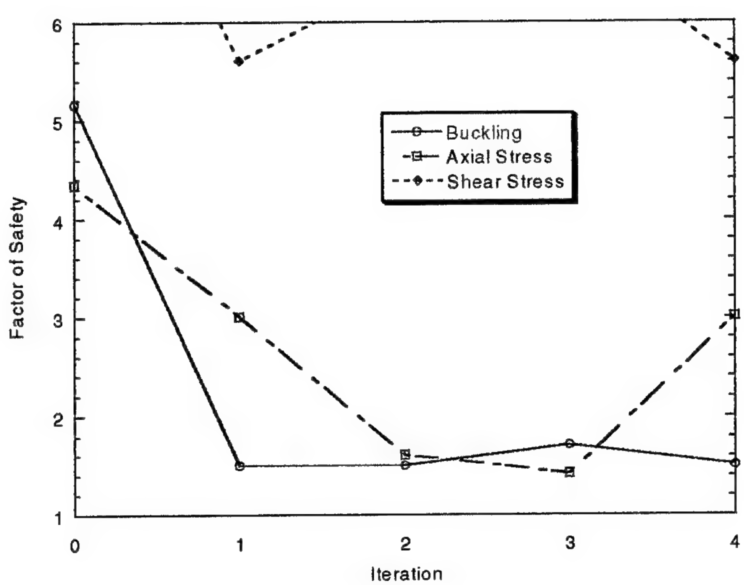


Figure 3-24 Factor-of-Safety History During Optimization of LCCW Missile

3.4.4 Shape Optimization Using Mechanica

Many codes exist which can optimize the thickness of a shell structure. A far more challenging problem is to optimize the shape of a structure. Part of the challenge is that geometric design variables require automated remeshing of the model. Also, optimization algorithms generally require computation of derivatives with respect to the design variables. This information can be computationally expensive to find in a conventional FEA code when the design variables are shape parameters.

A useful feature of Mechanica is the ability to perform shape optimization. The process is well suited to the analysis approach used in the code because the elements can represent complete geometric regions of the structure. The P-element formulation allows for a coarse discretization, and the element shapes can include geometric features such as arc segments.

An example problem was constructed to demonstrate this capability. Consider the bolt joint shown in Figure 3-25. The mesh generated by Mechanica is shown in Figure 3-26. The user may either employ the automated mesh generation, or control the mesh by hand. For this problem, the thickness is treated as a fixed quantity, while certain shape parameters are design variables. The joint width, edge distance from the pin, and the radius of the corner fillet are design variables. The objective is to minimize the joint weight, which is equivalent to minimizing the area. Only half the joint is modeled by taking advantage of symmetry.

Although Mechanica has a contact problem solution, the contact solution cannot be used in conjunction with an optimization run. Therefore, the pin load was approximated as a half-cosine distribution of radial pressure. This is a typical assumption used in analytic studies of loaded holes.

The material was assumed to be Graphite/Epoxy with a quasi-isotropic lay-up. Constraints were defined for the maximum stress in the x and y directions (50 ksi) and the shear stress (38 ksi).

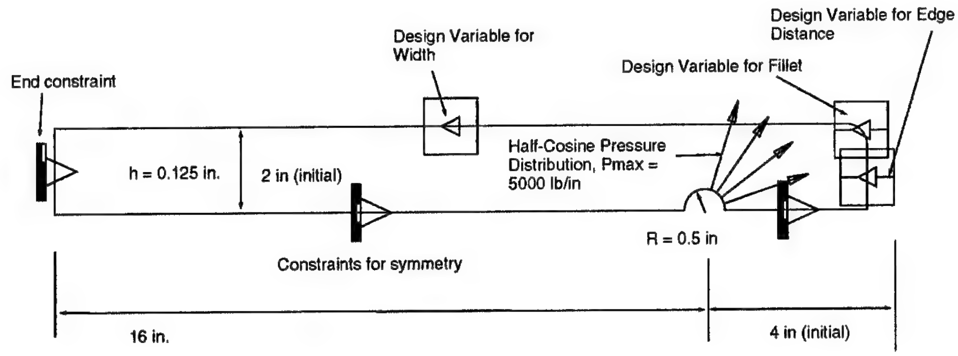


Figure 3-25 Idealization of Bolted Joint Shape Optimization Problem

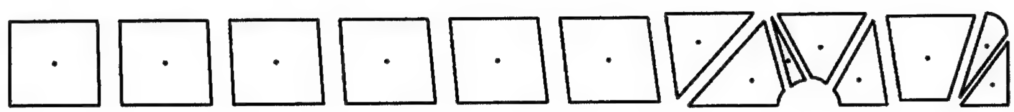


Figure 3-26 P-Element Mesh of Joint Using Automated Mesh Generation

Figure 3-27 shows the shape history for the joint, as the code iterates to find a minimum weight design. Some intermediate iterations have been left out of the figure because the changes in shape were minor.

Experiences with the Mechanica shape optimization demonstrate that the technology is useful and practical for certain types of problems. The main difficulty is in arranging geometric associations so that variations are not prevented by interference of interconnected geometric elements, or physically impossible configurations. These requirements limit the complexity of models, and the number of design variables that are suitable for geometric optimization.

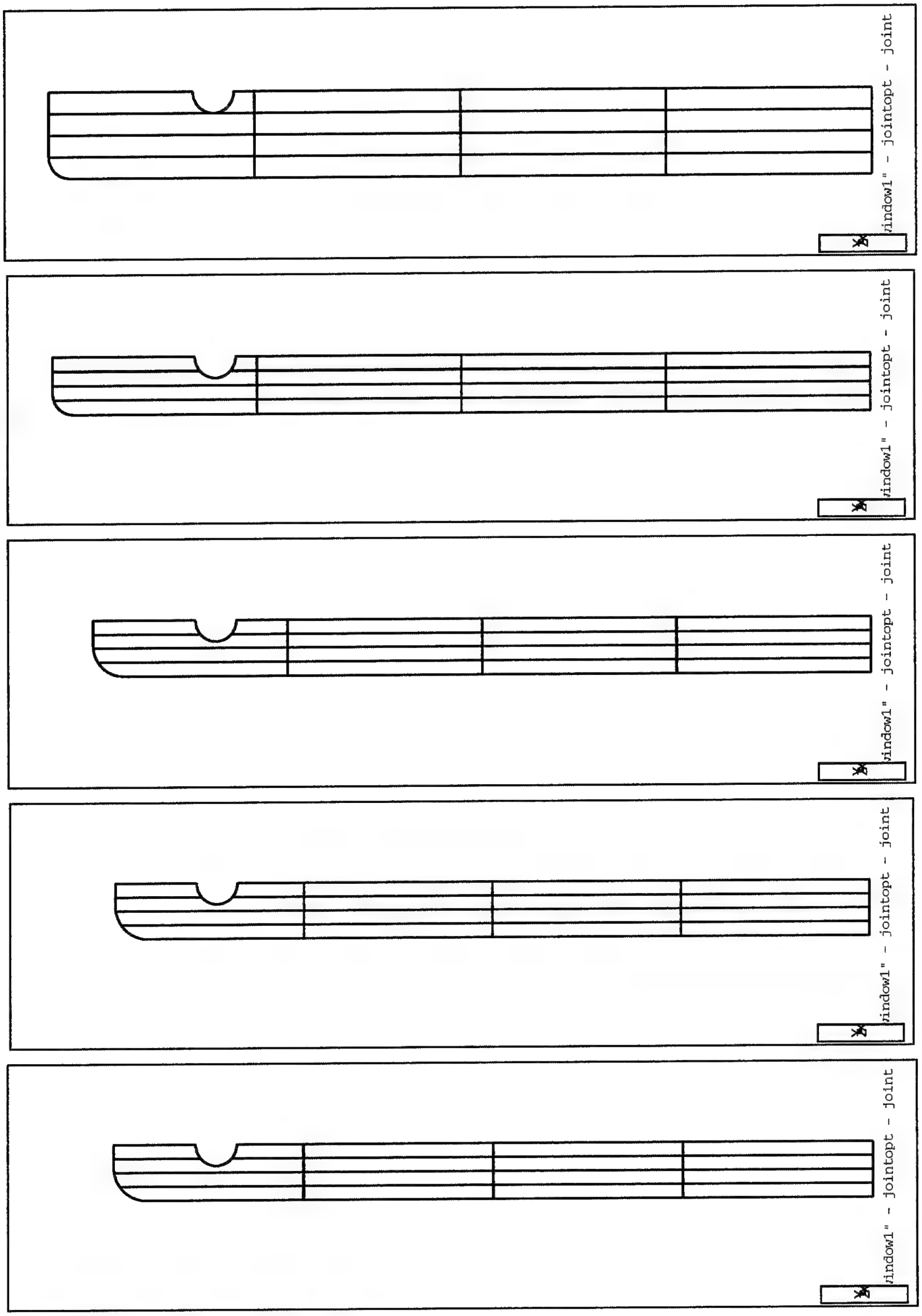


Figure 3-27 Shape History During Optimization of Joint Using Mechanica

4. PHASE II OPPORTUNITIES

4.1 INTRODUCTION

The goal of this program is to provide tools that can be used to examine the cost and performance trades associated with the introduction of new, high performance composite materials. The early Phase I work showed that the only practical way to identify the effects of material changes was to provide the engineer with automated structural design and optimization tools. These tools enable the engineer to make a material change, and track how the property changes affect the cost and performance of a structure. For example, it becomes possible to identify how much weight or cost is saved by varying fiber modulus or stiffener spacing.

Material trades often include substituting a material constituent such as the fiber or the matrix. These trades necessarily involve micromechanics in order to generate ply properties for a material that does not yet exist, or to complete a partially filled material database. One of the goals of the program is to integrate proven micromechanics models into the design and optimization process. Of high current interest are trades involving woven and braided textile forms. Micromechanics models for textile composites are less mature, but the need to perform trade studies between unidirectional laminates with textile constructions is obvious.

Cost optimization requires integrating a sophisticated cost model directly into the optimization process. Raw material cost is only a small fraction of the total cost of a structure. Typical cost models for prepreg laminates require knowing the number of plies, the ply placement, amount of cutting, and other detailed parameters. Cost cannot be optimized unless these factors are mathematically available to the optimization software.

All of these individual technologies exist in some form. However, they have not been integrated into a single, easy-to-use package which can be conveniently used in the preliminary design stage. Material trades and substitution are usually only an option during the early design phases of a project. This is the time when few details are known about the design, yet the effects of a material trade will only be evident when a fairly detailed design is derived. The solution to this dilemma is to provide software that combines a built-in knowledge base, sophisticated analysis tools, and formal optimization. This software will enable an engineer to evaluate multiple options, and make an informed decision. The software is tentatively being called *CompCost.*

4.2 TECHNOLOGY REQUIREMENTS IDENTIFIED FROM PHASE I

4.2.1 Engineering Approach to Rapidly Identifying Feasible Designs

An important lesson learned when using formal optimization algorithms is that the initial design must be reasonable, feasible, and near optimal. "Reasonable" means that manufacturing constraints, and engineering practice have been taken into account. By "feasible", we mean that all of the design constraints are initially satisfied. Many of the nonlinear optimization algorithms available have some capability to search for a feasible design, but experience shows that the initial design should be close to feasible in order to always obtain a useable solution. A "near optimal" design is desirable because some problems contain several local minima and most optimization algorithms cannot distinguish between a local and global minimum. In addition, the initial design should be close to the desired final outcome to maximize computational efficiency.

Each of these requirements imply that one needs to know the answer before using the sophisticated software. However, engineers have always had to deal with these design synthesis problems. In response, design procedures have been developed which lead one to feasible, near optimal designs (at least for weight). For example, in panel design, the engineer might go through the following steps:

- Determine the overall EA so that strain limits for strength are not exceeded.
- Pick a skin thickness. This implies a stiffener spacing to satisfy buckling.
- Enforcing a node specifies the stiffener EI.
- Create a stiffener with the required EI and EA, and perform approximate local buckling mode checks for the web and flanges.
- Do a detailed analysis to check for interacting buckling modes.

These same steps can be implemented in a rule-based program similar to expert systems. The rule based synthesis can be performed rapidly, allowing the user to "dial-in" many feasible designs before making a decision to optimize certain versions.

There are typically so many design variables available in the design of a composite panel, that one can find whole families of designs with nearly the same objective (cost or weight).

Using the approach outlined, combined with the optimization algorithm's propensity to find the closest local minima, will allow the engineer to explore these families of designs.

4.2.2 Realistic Stacking Sequence Capability

All of the optimization codes available treat the thickness of a layer as a continuous variable. The typical approach is to group all the plies of the same orientation into a single layer, as shown in Figure 4-1. For thin structure, this approach introduces significant error due to the important of stacking sequence in determining plate bending stiffness. In addition, the engineer is left with the problem of translating the optimized thicknesses into an integer number of plies, which must be placed in a sequence that does not violate any design rules. This translation from continuous thickness to real stacks can become difficult for thin laminates.

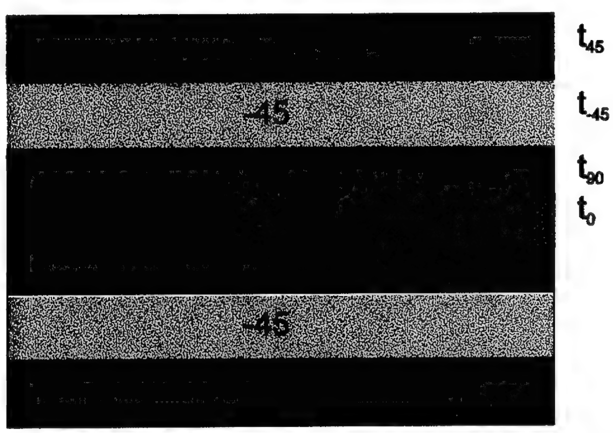


Figure 4-1 Stacking Sequence Idealization Typically Used for Continuous Variable Optimization Codes

Another aspect of this problem is the need for real stacking sequences in order to estimate cost. The cost of a part is a function of the number of plies that must be cut and placed, along with the ply area and perimeter. This information would not be available in a scheme that relied on continuous thickness optimization.

These are important shortcomings of current optimization practice. For these reasons, MSC has chosen to concentrate on optimization of actual stacking sequences using integer optimization techniques, combined with expert system software for applying rules. Figure 4-2 shows a screen from a *CompCost* prototype for defining the stacking sequence rules to be applied to

a laminate. These rules represent typical aerospace constraints on stacking sequence, and reflect concerns regarding ply cracking and delamination.

Using discrete plies involves a form of optimization called integer programming. Formal integer programming techniques are extensions of linear programming and, therefore, require linear constraint equations and objectives. These methods can be time consuming, and in addition the structural constraints are highly nonlinear. Therefore, we anticipate that less formal methods based on the modification of directed search methods and other heuristics will be applied.

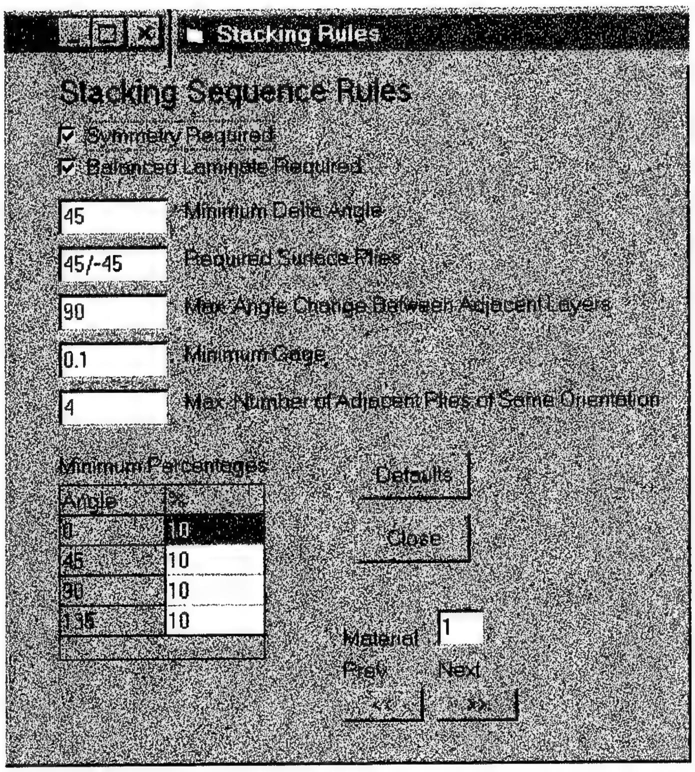


Figure 4-2 *Prototype Entry Form for Stacking Sequence Rules*

4.2.3 Integrated Micromechanics

In order to perform material trades, one must be able to examine substituting constituents of a composite. For example, what is the effect of changing the matrix while keeping the fiber constant? This capability can be added to the code by incorporating MSC's micromechanics

models. These models allow the user to determine ply properties from the properties of constituents, and to estimate failure based on the stress state within the constituents.

Another use of micromechanics is the ability to intelligently fill-in missing data from a property set. This capability was demonstrated in MSC's "Intelligent Database Program" [4]. The intelligent database uses known data to best-fit constituent properties based on rigorous micromechanics equations. From the same micromechanics relations, the unknown properties can then be estimated. An example of this capability is shown in Figure 4-3. The ability to complete a data set is crucial in a program that will be used to evaluate emerging materials for which there is limited data.

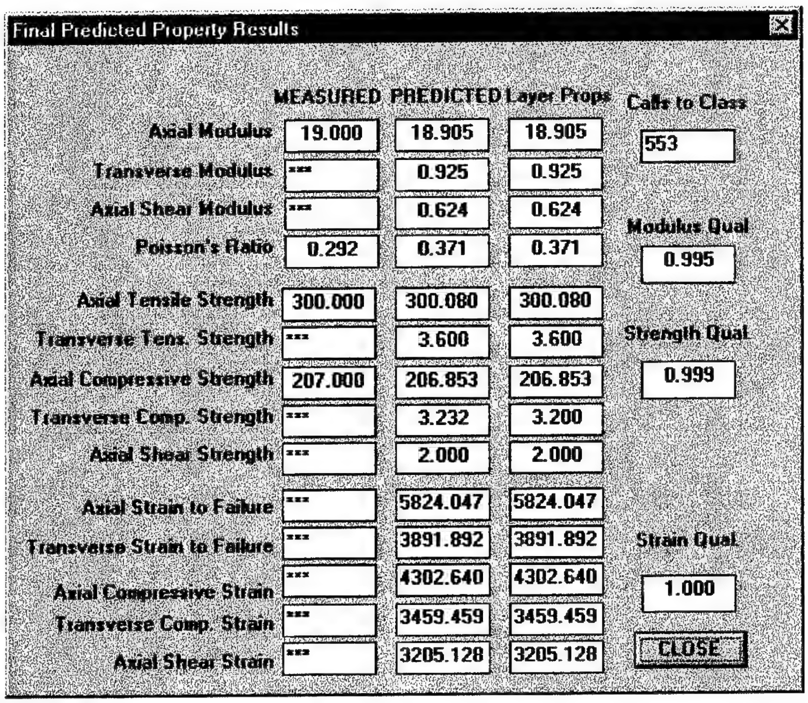


Figure 4-3 Example of Material Property Completion Using Micromechanics Models

4.2.4 Cost Models

Optimization of a composite structure cannot be performed on the basis of raw material costs alone. The cost is a strong function of the part complexity and required labor hours, as shown in Figure 3-17. A simple, relative cost model can be generated on the basis of:

- Raw material cost

- Cost of cutting and placing a ply
- The complexity of a stiffener (number of bends, concave versus convex surfaces, number of flanges)
- Fixed cost per stiffener

A representative screen from a software prototype (Figure 4-4) shows the input for a typical cost model. These factors are combined with raw material costs. While modeling at this level misses many of the process steps that go into a composite structure, this level of detail allows for comparison between different types of panel construction (sandwich, stiffened), different types of stiffeners, and different stiffener spacings. The complete system will be able to demonstrate how material changes effect the structural performance and cost. For example, a stiffer, but more expensive material could potentially reduce the number of stiffeners required, and thus reduce total cost.

It is evident that the cost model must be built directly into the analysis being passed to the optimizer. Computing cost of a minimum weight design will not, in general, yield the minimum cost design.

The code is capable of optimizing for cost or weight independently. In order to combine cost and weight into a single function, a value must be placed on the relative merit (in terms of dollars) of saving a pound of weight. The combined objective function can be written

$$P_{objective} = e(W - W_{\min}) / W_{\min} + (C - C_{\min}) / C_{\min}$$

where W_{min} and C_{min} are the minimum weight and cost, respectively, and e is a weighting factor related to the value of saving weight.

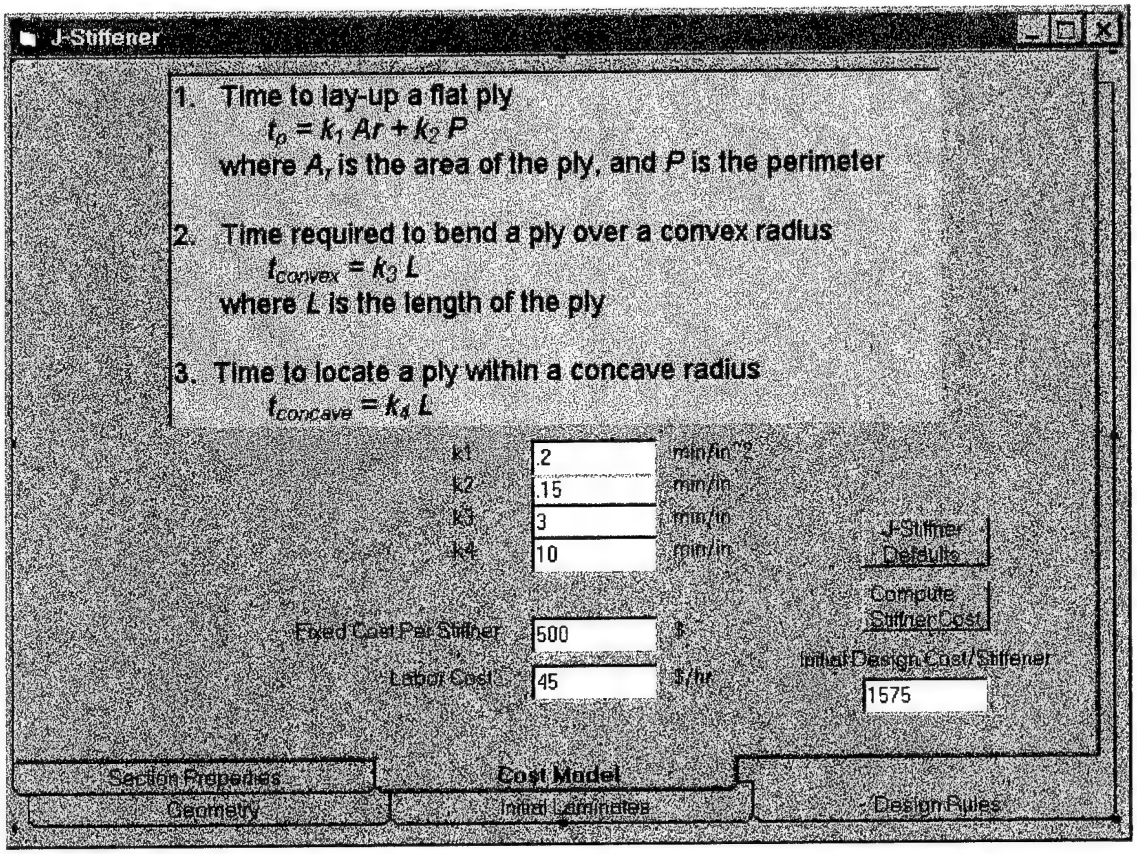


Figure 4-4 Prototype of Data Entry Form for Stiffener Cost Model

4.2.5 Panels Analysis

Optimization codes must use analyses that run quickly so that iterating for a minimum weight or cost design is practical. This requirement means that generality and speed must be balanced. Many aerospace structures can be approximated as prismatic, that is, uniform in cross-section along one axis (Figure 4-5). PASCO, one of the codes evaluated in Phase I, uses this assumption, combined with an exact strip analysis. Figure 4-6 shows a buckling solution from PASCO, taken from the Phase I studies. The exact analysis is elegant, but imposes a number of restrictions on the types of problems that may be solved. One problem is that finite length boundary conditions are not correctly imposed for a shear load. Another problem is the skin and stiffeners cannot have different end boundary conditions. For example, in many designs, the stiffeners are free at the ends, while the skin is supported. These constraints limit the value of the solution for realistic structures.

Another approach is to use a completely general finite element (FE) technique. This FE approach does not have the limitations of the classical strip method, but in general is too time consuming for an automated optimization tool.

MSC proposes a third approach that uses the prismatic assumption and strip analysis, but combines this approach with a more general P-element solution which removes the restrictions imposed by the closed-form method. The P-element method uses high order polynomials to represent the deflections. Convergence can be monitored and controlled by increasing the polynomial order. Preliminary studies indicate that this method will be sufficiently efficient to allow for trade studies and optimization on a desktop computer.

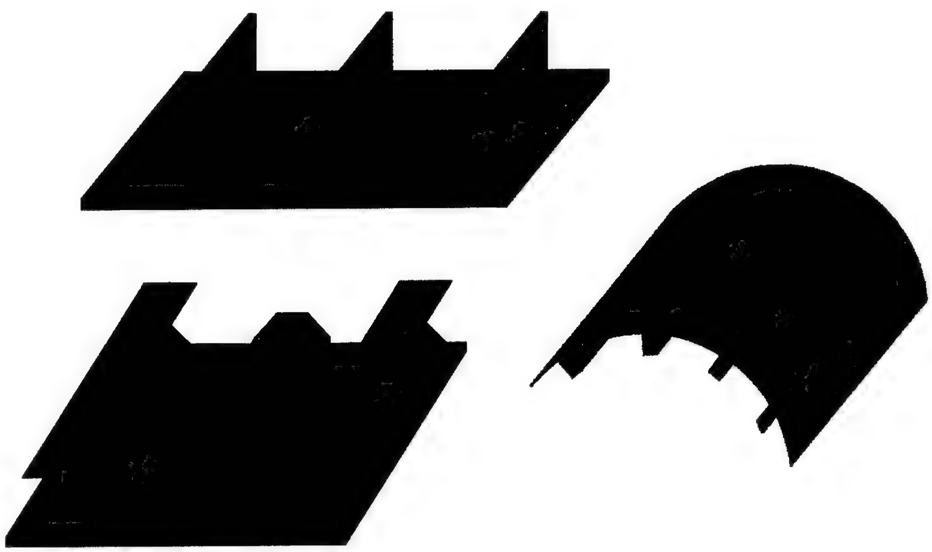


Figure 4-5 Typical Prismatic Structures

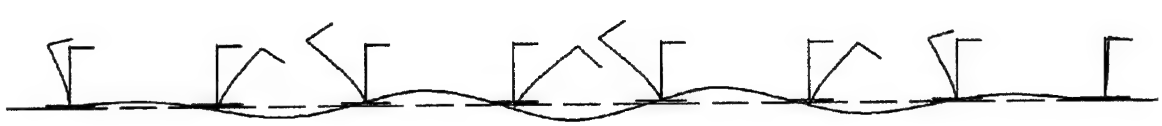


Figure 4-6 Buckling Mode Shape of J-Stiffened Panel From PASCO Analysis

4.2.6 Additional Failure Modes and Constraints

Optimization codes typically use simple structural constraints such as maximum allowable strain and buckling. Real aerospace structures have additional constraints and failure modes that will be more heavily impacted by material changes. These include failure around holes, and compression after impact. The failure around a hole is a function of both the material strength, and the laminate stacking sequence. Compression after impact is largely a function of the material toughness. Simple models can be implemented to capture the physics of these constraints, and make them part of the optimization process.

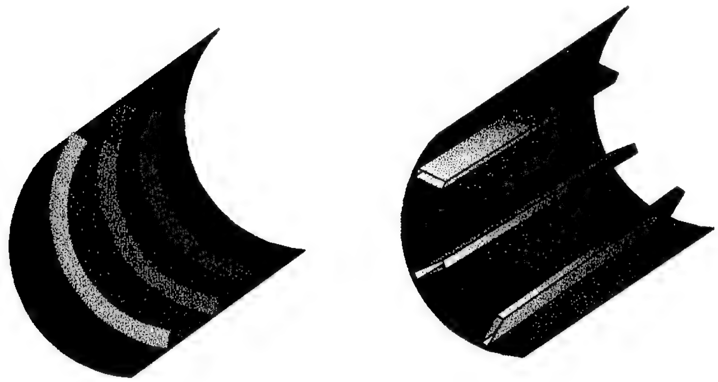
4.3 PHASE III PRODUCT DEFINITION

4.3.1 PC Software Package

The Phase II effort would focus on creating a Windows based optimization tool for the simultaneous cost and weight optimization of typical composite structures. The tool designed will provide rapid design trades at a level of detail sufficient to identify cost and performance drivers associated with material properties and fabrication process. The tool will provide an easy-to-use graphical interface that allows for extensive interaction between the user and the analyses.

4.3.2 Applicable Structures

The focus of this program will be on developing analysis modules for prismatic shell structures. This class of structures allows for mathematical simplifications that enable the software to run efficiently on desktop computers. In addition, this class is broad enough to cover most of the structural forms of interest to composites engineers in the aerospace industry. Models developed by MSC will include panel curvature both in the constant-section direction, and normal to that direction. Curvature in the constant-section direction allows for stiffeners in the hoop direction of a cylindrical structure. Curvature normal to the constant-section direction allows for stiffeners longitudinal to a cylindrical structure (Figure 4-7). Note that this capability makes the analysis applicable to blended body airframes being considered for next generation military aircraft.



(a) (b)

Figure 4-7 Prismatic Structure is Curvature in Prismatic Direction (a), and Normal to Prismatic Direction (b)

4.3.3 Technologies Employed

The analyses tools being planned require the development and maturation of several new technologies. These include:

- ***First-Principles cost modeling from lay-up and geometric details.*** This tasks involves establishing a framework that allows cost data to be entered into the program, and subsequently, incorporates this information into the optimization. Representative data for a limited number of forms and processes will be incorporated in the prototype given to NAVAIR.
- ***P-Element based shell analysis for thick, curved, stiffened panels.*** Thick plate theory will be required to accommodate sandwich structures. MSC will also examine the feasibility of adding a first-order postbuckling approximation to the analysis.
- ***The incorporation of knowledge-based expert system concepts.*** In order to handle the logic of initial feasible designs, stacking sequence rules, and manufacturing constraint rules, modern expert system concepts will be employed to speed development, and make future upgrades possible.
- ***Optimization algorithms with mixed continuous and integer design variables.*** This class of optimization problems is notoriously difficult to solve efficiently using formal procedures. The strategy will be to apply physics based heuristic rules to speed the integer optimization process.

- ***Property set completion for emerging materials.*** Property sets can be completed using a micromechanics based optimization algorithm. MSC has demonstrated this technology, but it needs further maturation for commercialization.
- ***Manufacturing constraints and micromechanics of textiles.*** It is evident that textiles will be used more extensively in future aircraft structure, both to improve performance and reduce costs. An effective code must be able to compute properties based on weaving or braiding parameters, and determine fabrication parameters for costing models.
- ***Solutions for notched strength and compression after impact.*** In order to quantify the effects of material changes, the code must be able to perform analyses of those failure modes most influenced by details of the material performance. Existing models must be reviewed and brought to maturity.

4.3.4 Typical Use Scenarios

A major emphasis in this program will be on ease-of-use. Methods for improving the ease-of-use include a graphical user interface (GUI). The interface design is important because it can make the program self documenting. Simple graphics can be used to explain each input parameter. Figure shows the input window for the geometry of a typical stiffener. Other ease-of-use features include on-line documentation, and extensive reporting generation capabilities.

The code could be used in a variety of scenarios ranging from user controlled standard panel analysis, to nearly automated optimization. Figure 4-9 shows some of the steps that might be involved in a typical analysis sequence. The user must be able to control the evolution of the design at any stage to insure a practical structure is being developed. The overall idea is to allow the user to make certain global trades, such as substituting a new material, and allow the computer to redesign the structure based on the new input. For this scenario to work effectively, the code must be able to maintain an internal database of designs and results so that the user can backtrack to select versions that were of most interest in a final report.

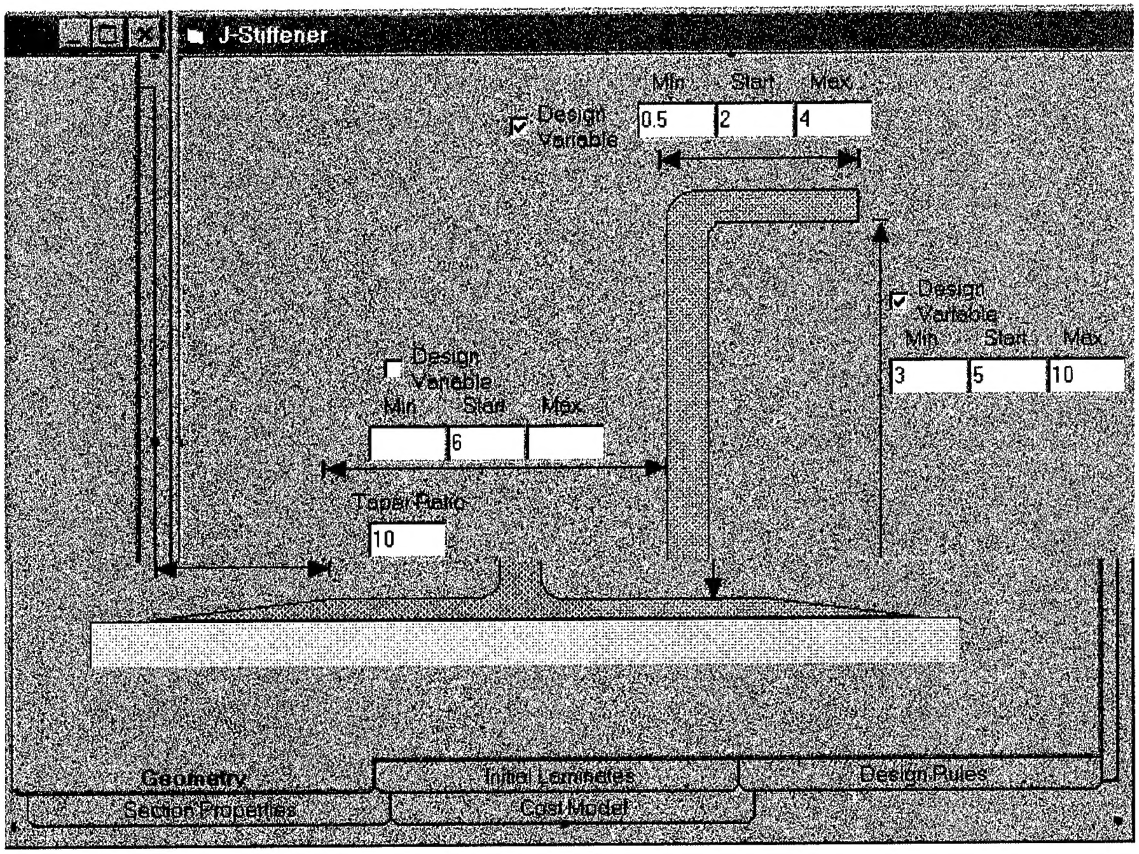


Figure 4-8 Prototype of Data Entry Form for Stiffener Geometry

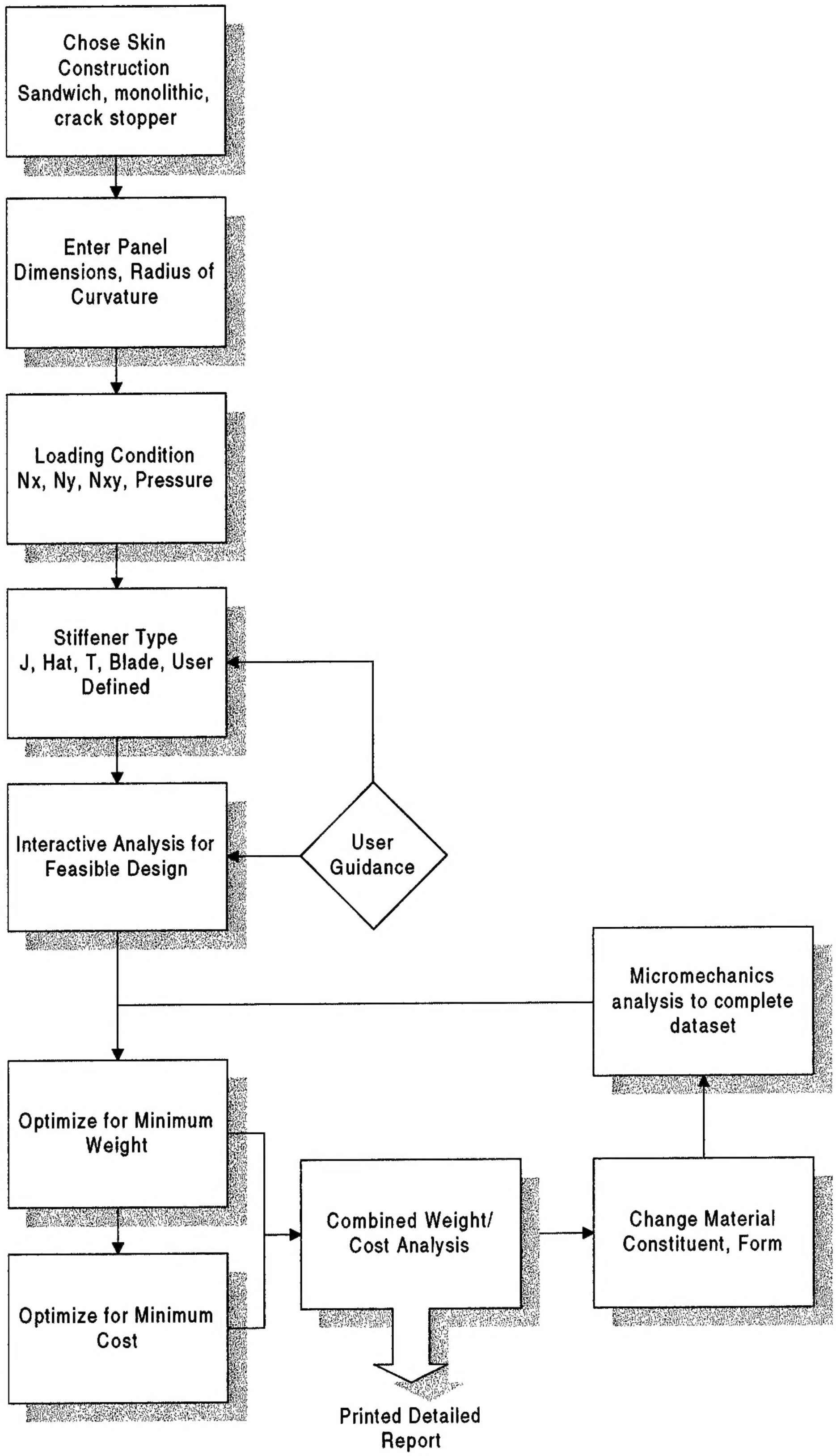


Figure 4-9 Typical Path for Using CompCost

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